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HIGH-β MODIFICATION OF MAIN RING LONG STRAIGHT INSERTION

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The magnet aperture width of the main ring is determined mainly by requirement for resonant beam extraction. For example, aperture widths of bending magnet B1 required at injection and extraction are as follows:

	At injection (10 BeV)	At 200 BeV	For Extraction
Emittance	1.58"	0.37"	3.15"
Momentum spread	0.40"	0.04"	0.04"
Poorfield region	0.50"	0.50"	0.50"
Close-orbit errors	1.16"	1.16"	1.16"
	3.64"	2.07"	4.85"

where the emittance contribution to aperture width requirement for extraction is obtained by assuming that the extraction septum is placed at 3 cm from the beam center line and that the beam amplitude growth for jumping septum is 1 cm. Thus, we see that if it were not for extraction an aperture width of 3.7" (instead of 5.0") would be adequate. For extraction the beam needs to be wide only at the extraction septum located at the beginning of the long straight insertion. The suggestion made by D. Edwards of Cornell of using a lattice in which β_x at the extraction point is higher than that elsewhere around the ring has, therefore, an immediate application here.

With such a high-β insertion and resonant extraction when the beam width is blown-up by the resonance to a large enough value at the septum for extraction at 200 BeV the aperture width requirement in the normal cells would not exceed 3.7". Thus, the aperture widths of the magnets in the normal cells could be kept small. Various conditions and considerations leading to the special design presented here are the following:

(1) The ground rule adopted for this study is to try obtaining high-β by modifying only the field gradients of the guadrupoles in and next to the present long straight insertion so that the insertions could be operated as normal insertions for most part of the acceleration cycle and that the high-β modification would be turned on only near the final energy (200 BeV) for extraction.

(2) Since the extraction septum is near the beginning of the insertion to get a high β_x at that location we have to modify some normal cell quadrupoles immediately ahead of the insertion. Also to keep the phase advances in the vertical and the horizontal planes in the insertion approximately equal we want to maintain the antisymmetric feature of the insertion. This means that we have to simultaneously modify the normal cell quadrupoles immediately after the insertion in an antisymmetric manner.

(3) Attempts of including only one normal cell quadrupole 1/2 cell upstream and the corresponding one downstream of

the insertion among those whose gradients are to be modified did not produce any arrangement with desirable or acceptable β-function. The trouble is that 1/2 cell is too short a distance for the upstream normal cell quadrupole with reasonable gradient to produce a significantly higher β_x at the beginning of the insertion and that when β_x at the beginning of the insertion is made somewhat higher its value in the downstream set of matching quadrupole quadruplet becomes prohibitively high. It was, therefore, necessary to modify the gradients of four normal cell quadrupoles, two upstream and two downstream of the insertion, in addition to those of the quadrupoles in the insertion. It was then possible to obtain acceptable β-functions with maximum β_x occurring at the first quadrupole of the insertion and having values a factor of 10 or more higher than that in the normal cells.

(4) The gradients of the first and the last quadrupoles of the insertion are adjusted to give an almost flat high β_x between the first quadrupole and the first matching quadrupole quadruplet. This is the space where the electrostatic extraction septum is located and where a flat high β_x is desired for optimum extraction efficiency. The gradients of the two sets of quadrupole quadruplets are then adjusted to obtain matching.

(5) The betatron oscillation phase advance over the high-β modified insertion turns out to be larger than that

over the normal insertion. To keep the betatron oscillation wave numbers unchanged we have to reduce the phase advance in the normal cells by reducing the gradients of all the normal cell quadrupoles. The amount of phase advance reduction required depends on how many of the six long straight insertions are modified to give high β. Although only one high-β insertion is needed for the one extracted beam the large 20th harmonic gradient variation around the ring introduced by the one high-β insertion being very close to the ν value of about $20\frac{1}{4}$ produces a very high maximum dispersion width x_p. We have, therefore, chosen the case of 3 symmetrically located high-β insertions for which the 20th harmonic is absent and the harmonic closest to $20\frac{1}{4}$ is 21. This situation cannot be further improved by adding more high-β modified insertions. When the normal cells are modified to reduce the phase advance, of course both the normal-β insertion and the high-β insertion should be rematched to the modified normal cell.

For matching of betatron functions we used the computer program TRANSPORT and for the adjustment of phase advances and computation of β and x_p functions around the ring we used the program SYNCH. In Table 1 we give as an example the quadrupole gradients at 200 BeV for the unmodified case and the modified case of 3 normal-β and 3 high-β insertions with the high-β value of 600 m. Interesting orbit parameters for these cases are listed in Table 2. The β_x function for the insertion of the unmodified case and the normal-β and the high-β insertions of the modified case are plotted in Fig. 1.

The advantages of the high-β modification in reducing the necessary horizontal apertures of magnet in the normal cells are quite evident. However, from these tables and figures and from general considerations of orbit characteristics we note the following disadvantages of the high-β modification.

(1) For given field errors and misalignments of magnets the closed-orbit distortion is proportional to $\sqrt{\beta}$ and is, therefore, larger in the high-β insertion where β is high.

(2) The dispersion-width function x_p has negative values for the case with high-β modification. This in itself is not a disadvantage. However, the maximum x_p is higher with high-β modification, being 12.5 m compared to 5.2 m for the unmodified case. This means that more horizontal aperture must be allowed for the momentum width of the beam which may be troublesome if the momentum spread of the beam suffers sizable blow-up at transition crossing due to space charge forces.

(3) Depending on the order n of the resonance employed for extraction with given strength of excitation the horizontal oscillation amplitude growth per turn ΔA is given by

$$\frac{\Delta A}{\sqrt{\beta}} \propto \left(\frac{A_o}{\sqrt{\beta}}\right)^{n-1}$$

where A_o is the amplitude just before the last turn and is equal to the separation between the extraction septum and the beam center line. Therefore for third and higher order resonant extraction and for given separation between extraction septum and beam center line the amplitude growth for septum jumping is smaller for larger β. Of course, it is possible to increase A_o to recover or even to exceed the amplitude growth without the high-β modification. This, however, means that the horizontal aperture of the magnets in the high-β insertion must be larger than those of the unmodified case although the horizontal apertures in the normal cells could be smaller. This disadvantage was first pointed out by E. D. Courant (FN-163).

Table 1

(A) Normal cell

Quad	Length (m) No. Bending Mag.	Gradient at 200 BeV (kG/m) Unmodified	 Modified
2QF	2.1336 27.6098 [4B]	125.5593	119.1522
2QD	2.1336 27.6098 [4B]	-125.5593	-119.1522

Table 1

(B) Insertion section

Section	Quad	Length (m) [No. Bending Mag.]	Gradient at 200 BeV (kG/m) Unmodified	Modified Normal-β	Modified High-β
	2QF	2.1336	125.5593	119.1522	70.9491
		27.6098 [4B]			
	2QD	2.1336	-125.5593	-119.1522	-167.1048
		27.6098 [4B]			
INSERTION	QFL	1.31953	125.5593	119.1522	121.3438
INSERTION		28.42387 [3B]			
INSERTION — UPSTREAM MATCHING QUADRUPLET	QFL	1.31953	125.5593	124.0301	234.9311
INSERTION — UPSTREAM MATCHING QUADRUPLET		0.346202			
INSERTION — UPSTREAM MATCHING QUADRUPLET	QFL	1.31953	125.5593	124.0301	234.9311
INSERTION — UPSTREAM MATCHING QUADRUPLET		1.76075			
INSERTION — UPSTREAM MATCHING QUADRUPLET	QDL	1.31953	-125.5593	-122.7373	-215.4738
INSERTION — UPSTREAM MATCHING QUADRUPLET		0.29869			
INSERTION — UPSTREAM MATCHING QUADRUPLET	2QD	2.1336	-125.5593	-122.7373	-215.4738
INSERTION		50.80327			
INSERTION — DOWNSTREAM MATCHING QUADRUPLET	2QF	2.1336	125.5593	122.7373	215.4738
INSERTION — DOWNSTREAM MATCHING QUADRUPLET		0.29869			
INSERTION — DOWNSTREAM MATCHING QUADRUPLET	QFL	1.31953	125.5593	122.7373	215.4738
INSERTION — DOWNSTREAM MATCHING QUADRUPLET		1.76075			
INSERTION — DOWNSTREAM MATCHING QUADRUPLET	QDL	1.31953	-125.5593	-124.0301	-234.9311
INSERTION — DOWNSTREAM MATCHING QUADRUPLET		0.346202			
INSERTION — DOWNSTREAM MATCHING QUADRUPLET	QDL	1.31953	-125.5593	-124.0301	-234.9311
INSERTION		28.42387 [4B]			
INSERTION	QDL	1.31953	-125.5593	-119.1522	-121.3438
		27.6098 [4B]			
	2QF	2.1336	125.5593	119.1522	167.1048
		27.6098 [4B]			
	2QD	2.1336	-125.5593	-119.1522	-70.9491

Table 2

	Unmodified	Modified	
β_{max} in normal cell (m)	98.7	99.6	
β_{min} in normal cell (m)	26.6	29.3	
$\frac{\psi}{2\pi}$ across normal cell	0.197	0.186	
		Normal-β	High-β
β_{max} in insertion (m)	122.7	122.3	600
β_{min} in insertion (m)	26.6	29.3	2.9
$\frac{\psi}{2\pi}$ across insertion section contained in Table 1(B)	0.730	0.695	1.046
$x_{p\ max}$ (m) occuring in normal cells	5.2	12.5	
$x_{p\ min}$ (m) occuring in normal cells	1.3	-4.3	
x_p average (m)	2.7	3.9	
ν_x	20.28	20.21	
ν_y	20.32	20.25	
γ_{tr}	19.6	18.6	

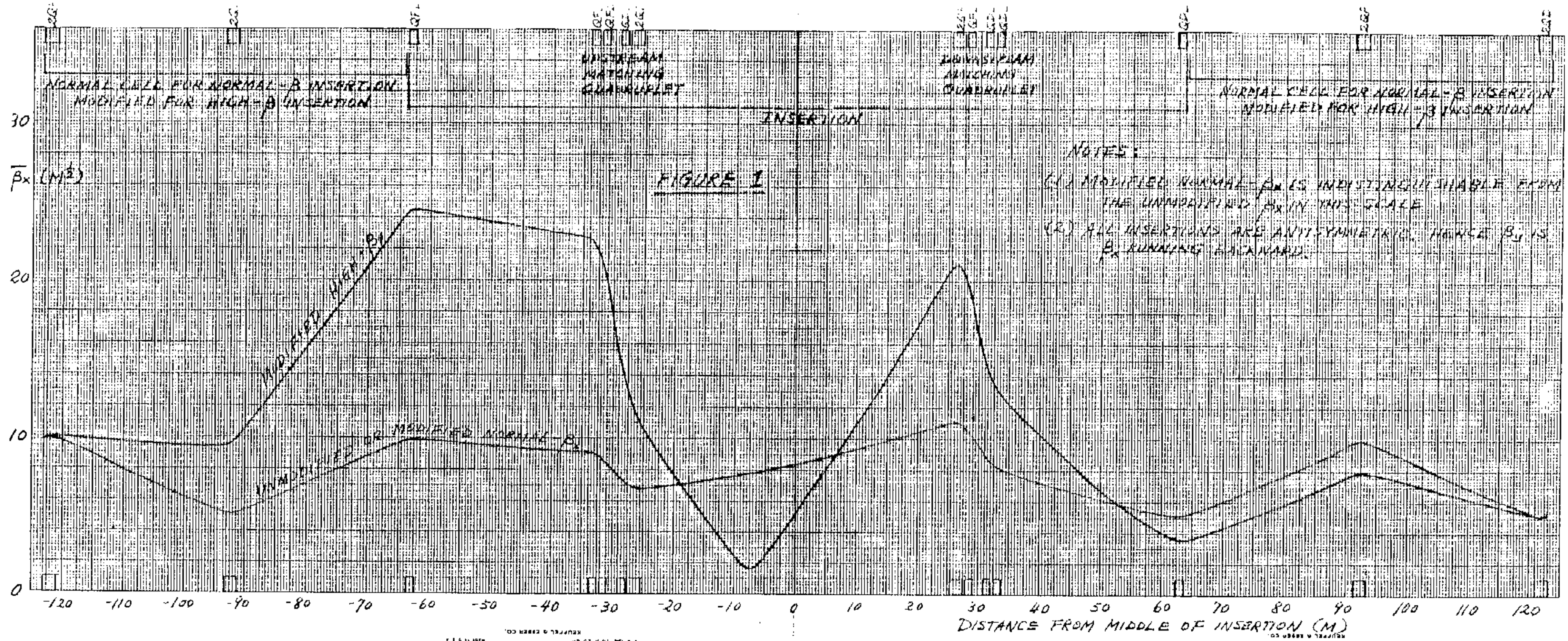
NORMAL CELL FOR NORMAL-β INSERTION
MODIFIED FOR HIGH-β INSERTION
UPSTREAM MATCHING QUADRUPLET
INSERTION
DOWNSTREAM MATCHING QUADRUPLET
NORMAL CELL FOR NORMAL-β INSERTION
MODIFIED FOR HIGH-β INSERTION
NOTES:
(1) MODIFIED NORMAL-β_x IS INDISTINGUISHABLE FROM THE UNMODIFIED β_x IN THIS SCALE
(2) ALL INSERTIONS ARE ANTISYMMETRIC, HENCE β_y IS β_x RUNNING BACKWARD.
$\overline{\beta}_x$ (M)
MODIFIED HIGH-β_x
UNMODIFIED OR MODIFIED NORMAL-β_x
0
10
20
30
-120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100 110 120
DISTANCE FROM MIDDLE OF INSERTION (M)

FIGURE 1